REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 18-05-2011	**2. REPORT TYPE** Briefing Charts	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE

ALREST High Fidelity Modeling Program Approach

5a. CONTRACT NUMBER FA9300-10-C-0010

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5f. WORK UNIT NUMBER 33SP07KR

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL-RZ-ED-VG-2011-168

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/RZS
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Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)

AFRL-RZ-ED-VG-2011-168

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited (PA #11125).

13. SUPPLEMENTARY NOTES

For presentation at the Joint French/German/United States Symposium on Liquid Rocket Combustion Instability, London, UK, 15-16 Jun 2011.

14. ABSTRACT

The U.S. Air Force Research Laboratory (AFRL) is working with Pratt & Whitney Rocketdyne (PWR) to develop improved computational tools to predict better combustion stability of hydrocarbon-fueled liquid rocket engines. The Advanced Liquid Rocket Engine Stability Technology – High Fidelity Model (ALREST-HFM) code will be designed to improve the prediction of combustion instability using Computational Fluid Dynamics (CFD). Pratt & Whitney Rocketdyne has assembled a team that includes Professor Suresh Menon and coworkers at the Georgia Institute of Technology who have developed the LESLIE3D for supercritical hydrocarbon combustion; HyPerComp, Inc., a small business located in Westlake Village, CA, that specializes in the research and development of computational tools for fluid mechanics and combustion; and United Technologies Research Center (UTRC) in East Hartford, CT, who have extensive experience with hydrocarbon combustion and fluid properties. Pratt & Whitney Rocketdyne will lead the code development and provide its expertise in hydrocarbon-fueled rocket engines.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Dr. Douglas Talley
Unclassified	**Unclassified**	**Unclassified**	SAR	24	**19b. TELEPHONE NUMBER** *(include area code)* N/A

ALREST High Fidelity Modeling Program Approach

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ALREST High Fidelity Modeling Program Approach

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Georgia Institute of Technology
June 15, 2011

Importance of Combustion Instability as Issue in LRE Development

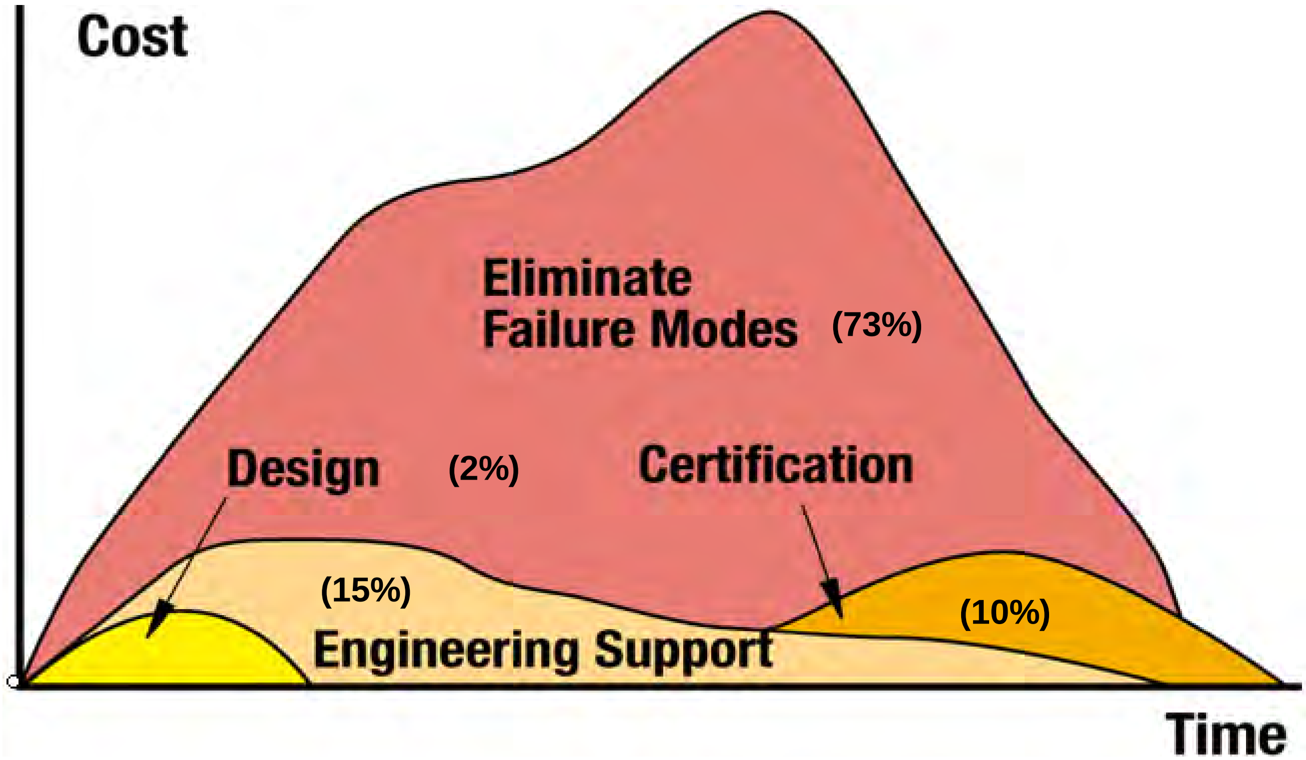
Damage to Rocket Chamber from Combustion Instability

- PWR Apollo-Era F-1 Engine Required Over 2000 Full Engine Tests to Attain Stable Design
- Several Billion Dollars in Current Terms

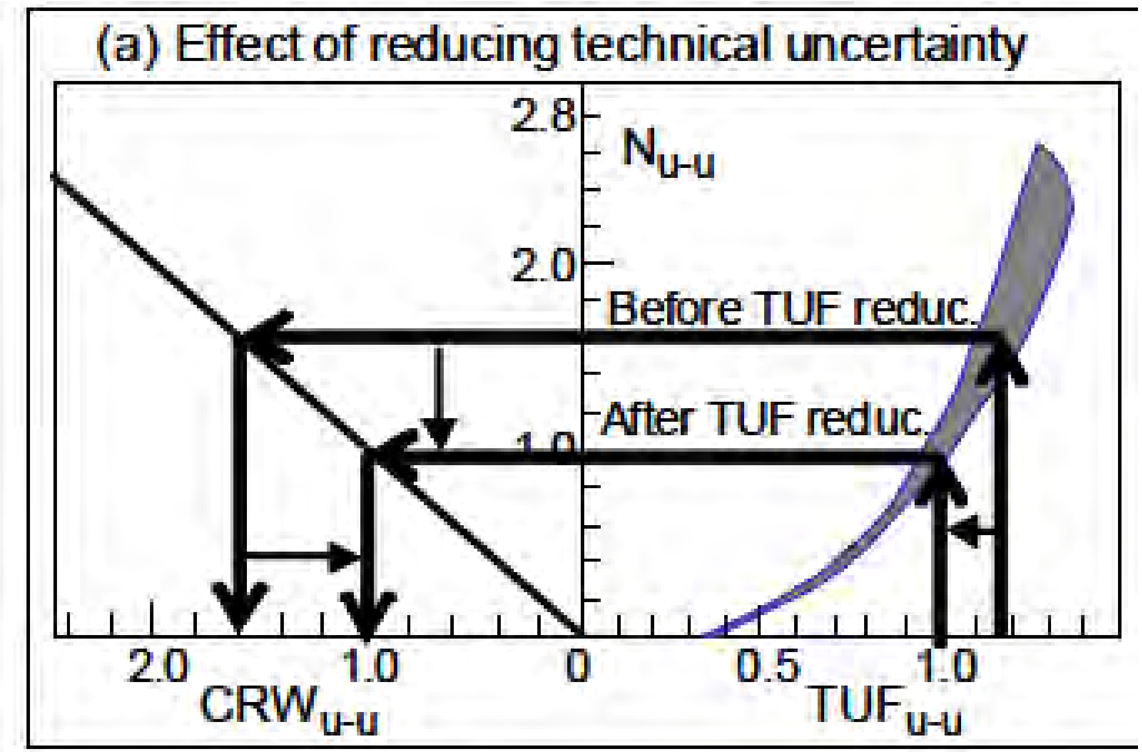
Genesis of ALREST-HFM Program

- **Potential Attractiveness Of Liquid Hydrocarbon Engines For Boost Applications**
- **Propensity Of Hydrocarbon Engines For Combustion Instability**
- **Air Force Initiated Hydrocarbon Boost Demo Program To Develop Technology For Next Hydrocarbon-fueled Boost Rocket Engine**
- **ALREST-HFM To Create Tools Which Can Provide Nonlinear, Chamber-level Stability Predictions For Hydrocarbon-fueled Engines To Help Industry In The LRE Design/Development Process**

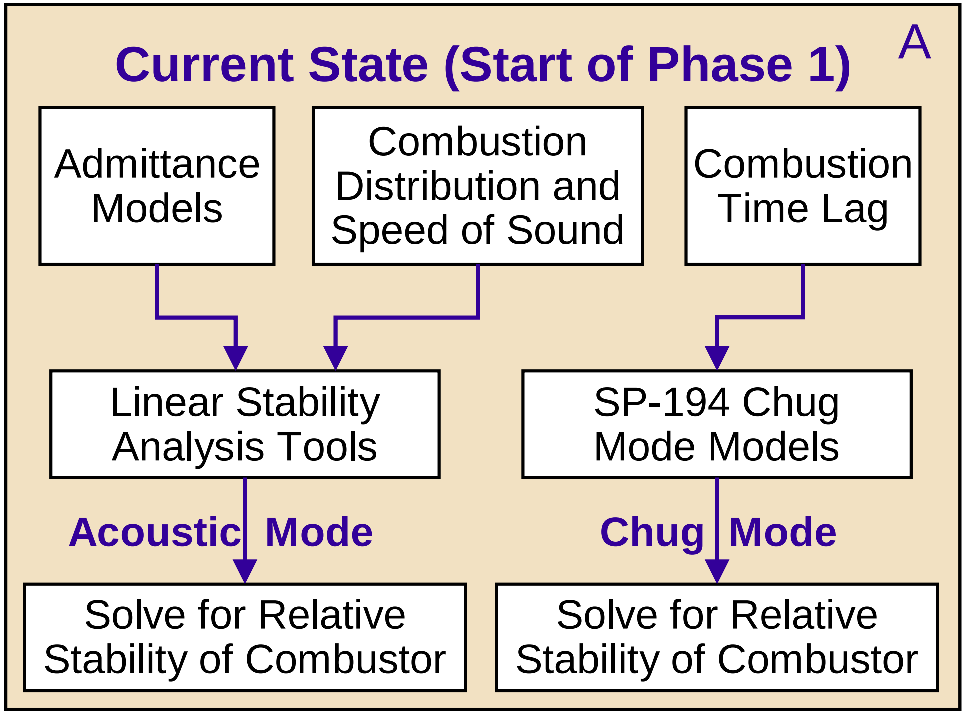
Cost Structure of Previous LRE Development Programs



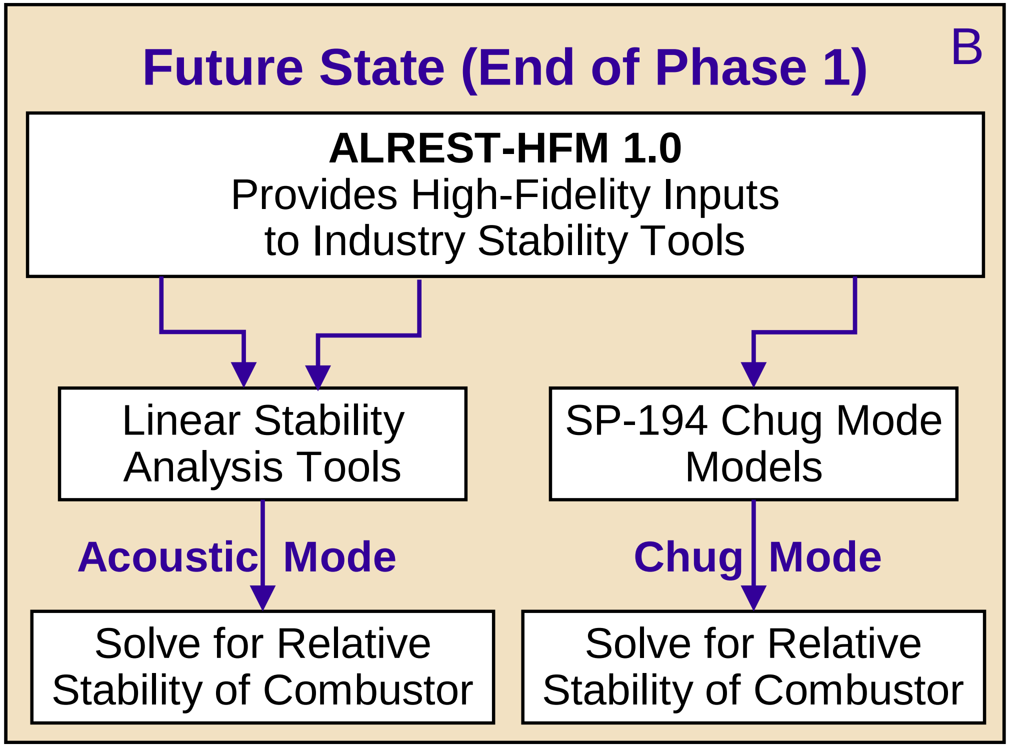
Rationale for Importance of Use of High Fidelity Analysis Tools



Current State for Combustion Instability Prediction in Rocket Engine Development in Industry



Future State for Combustion Instability Prediction in Rocket Engine Development in Industry



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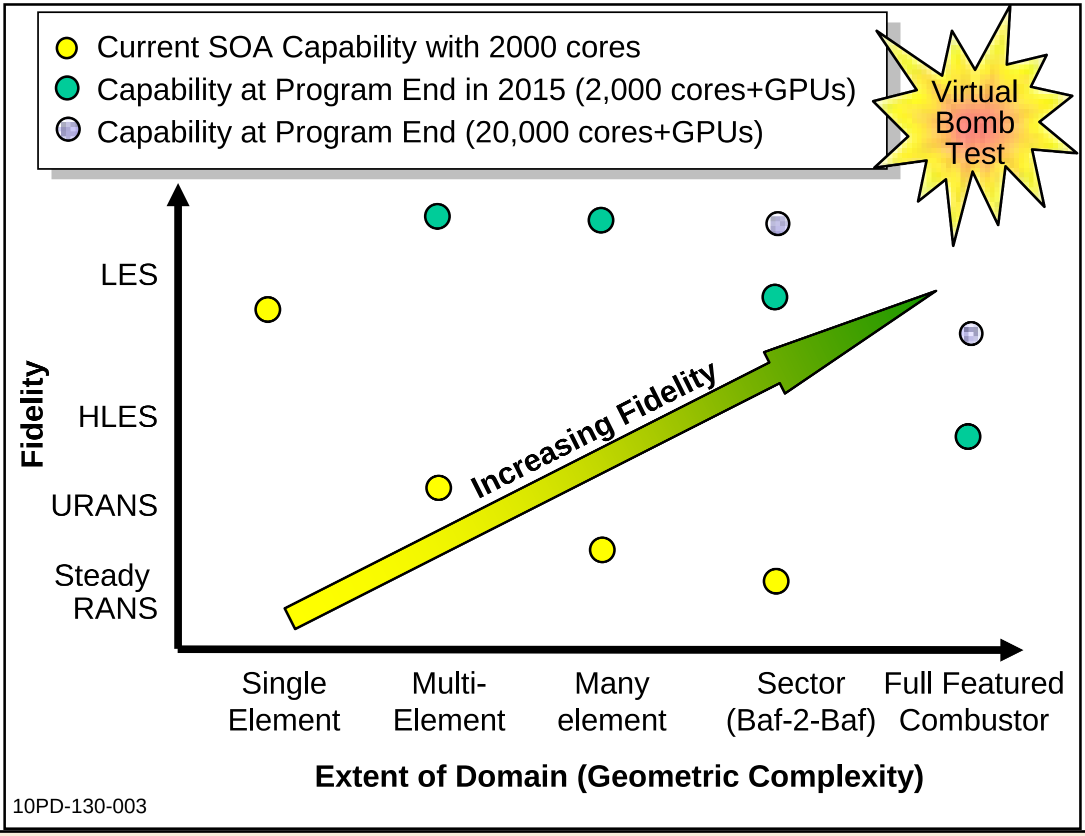
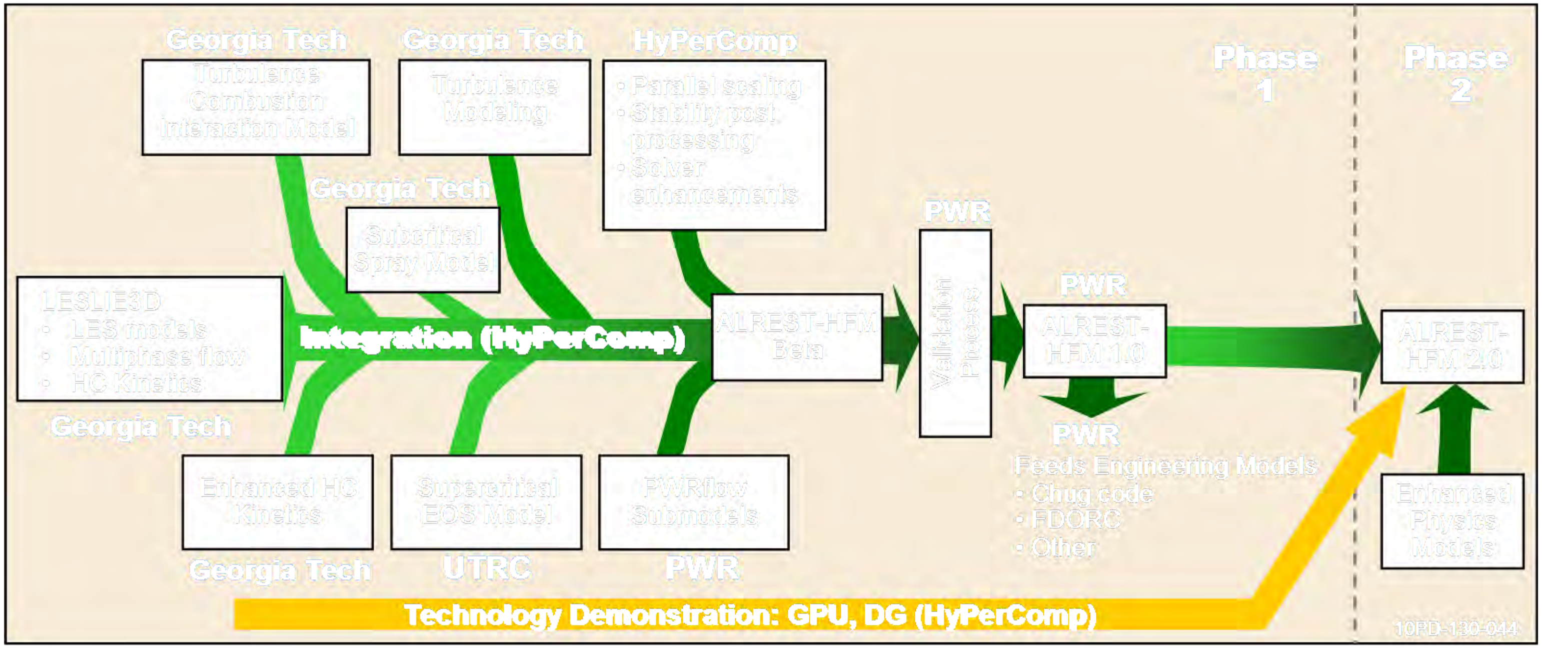
Future Vision

ALREST-HFM x.x

High fidelity CFD replaces current industry standard tools



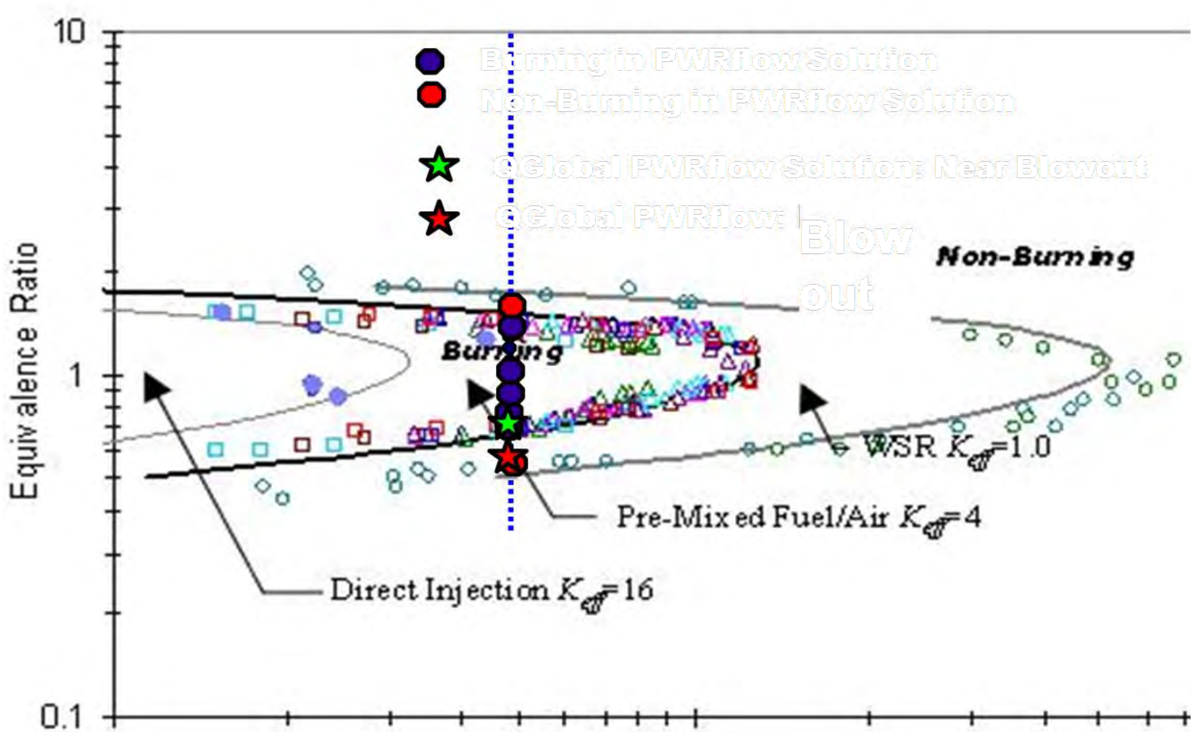
ALREST-HFM Development Plan and Team



Marriage of PWR PWRflow RANS and Georgia Tech LESLIE3D Codes

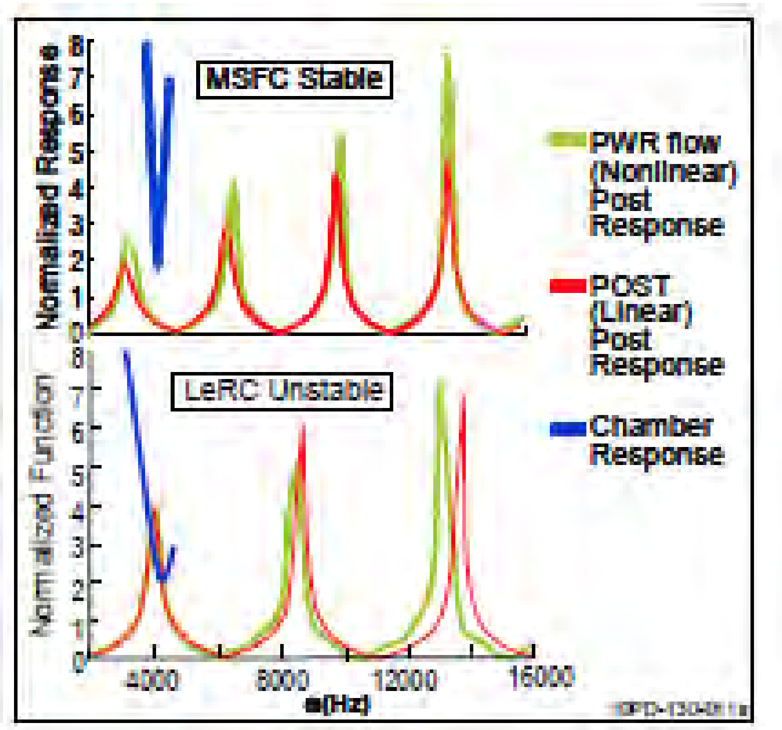
	Discretization	Solution Advancement Schemes	Types of Grid	Turbulence Modeling	Kinetics Models	Fluid Properties	Turbulence-Chemistry Interaction Modeling	Discrete Multiphase Modeling	Dispersed Multiphase Modeling
LESLIE3D	Hybrid HLC/E	Currently Explicit Predictor-Corrector Temporal 2nd-Order	Structured; Structured-Unstructured Cartesian	Subgrid Scale K-KL and K-Δ	Variety of Hydrogen and Hydrocarbon Models for Gas Turbines, Ramjets, and LRE's	Mixtures of Calorically Perfect Gases and Mixtures of Peng-Robinson Fluids with Detailed Species Properties	Variety of RANS and LES modeling ranging from flamelets, eddy breakup modeling to LEM (Linear Eddy Modeling)	Detailed Level Set model for drop breakup with interface refinement	Lagrangian Droplet Model with drop breakup and evaporation exercised on gas turbine analyses
PWRflow	Cell-Based Limiting with Rusanov, Roe, and FORCE (large density differences) Riemann solvers	Diagonalized and Precond-itioned/Nonpreconditioned Point Implicit, Multigrid and Chunk G-S Global Implicit	Unstructured	Goldberg, Menter, and Spalart-Allmaras 1-Equation RANS Models; Anisotropic k- ε Model	1- and 2-step global, quasiglobal, and mechanistic models for a variety of hydrocarbons fuels and hydrogen including RP	Perfect Gas, Equilibrium Air, Mixtures of Calorically Perfect Gases and Mixtures of Redlich-Kwong and Peng-Robinson Fluids	Assumed pdf Model based on k-ε-g Model in NASA/LaRc Vulcan code	Level Set model for drop breakup employed on some selected problems	Lagrangian Droplet Model with breakup now being tested on gas turbine problems

Quasiglobal Modeling Provides Cost Effective Solution to Tip Flame Stability Prediction



- Finite-Rate Propane Kinetics
- 11-Species Quasiglobal Modeling Approach
- 41-Species, 163-Reaction Mechanistic Model

Postprocessing Key Element of ALREST-HFM Tool



- Open Loop LOX Post Response Function
  - Unsteady PWRflow Supercritical Full Navier-Stokes CFD Analyses
  - 82-element Jensen LOX-Hydrocarbon Stability Tests
  - Experience with Upstream BC Issues

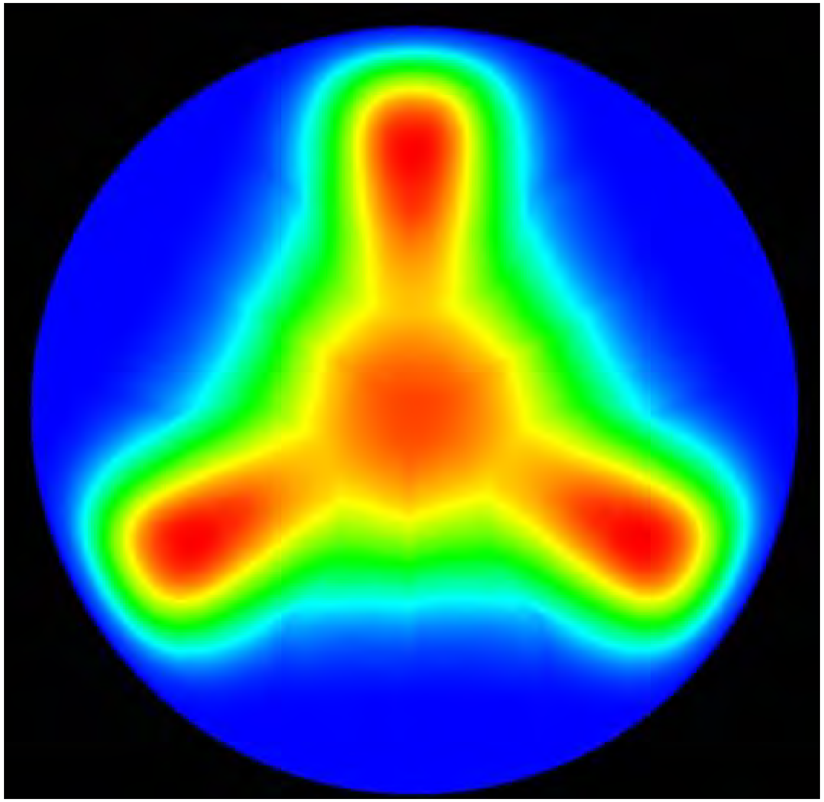
- Presupplied Functions and User Defined Functions
  - Rayleigh integral
  - Frequency Domain Quantities
  - Response Functions
  - Nozzle and Manifold admittances

Combine Demonstrated Capabilities of PWRflow and LESLIE3D

- **LESLIE3D**
  - **Successful At Predicting Flame Dynamics For Gas Turbines, Scramjets And Rocket Injectors**
- **PWRflow**
  - **Designed For Steady And Unsteady RANS**
  - **Successful In Predicting η_{c^*} And Wall Heat Transfer In Single And Multiple Injector Chambers**

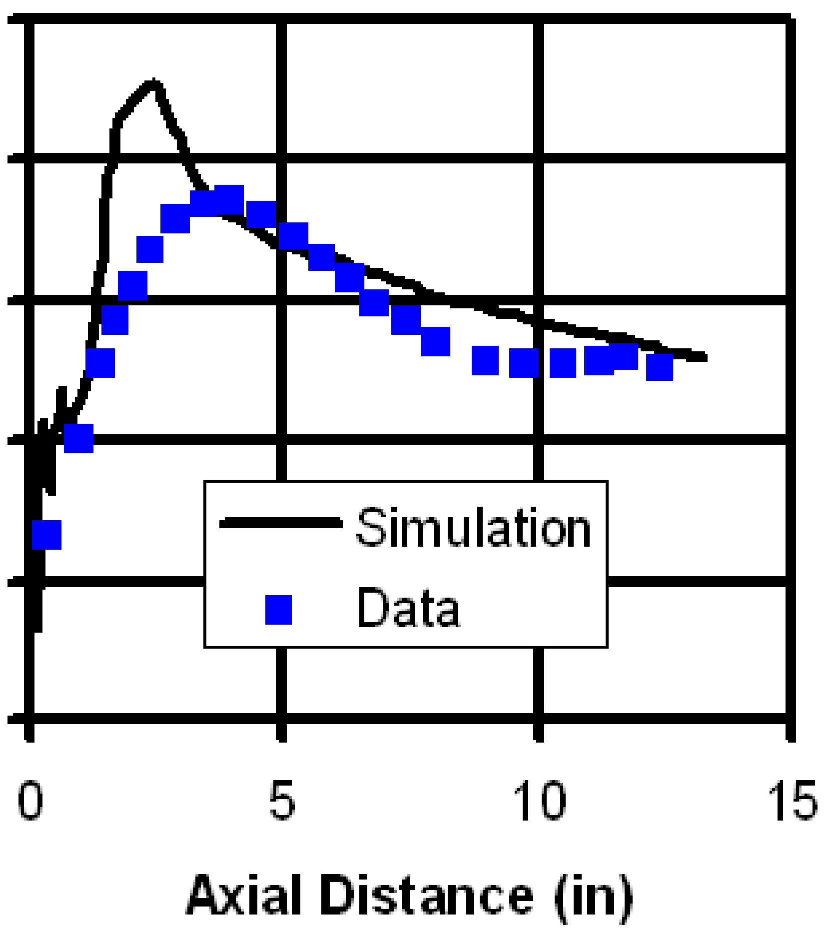
PreContract PWRflow Examaples

Cross Section of LOX Stream for 3-Element PWRflow Analysis of PSU Test

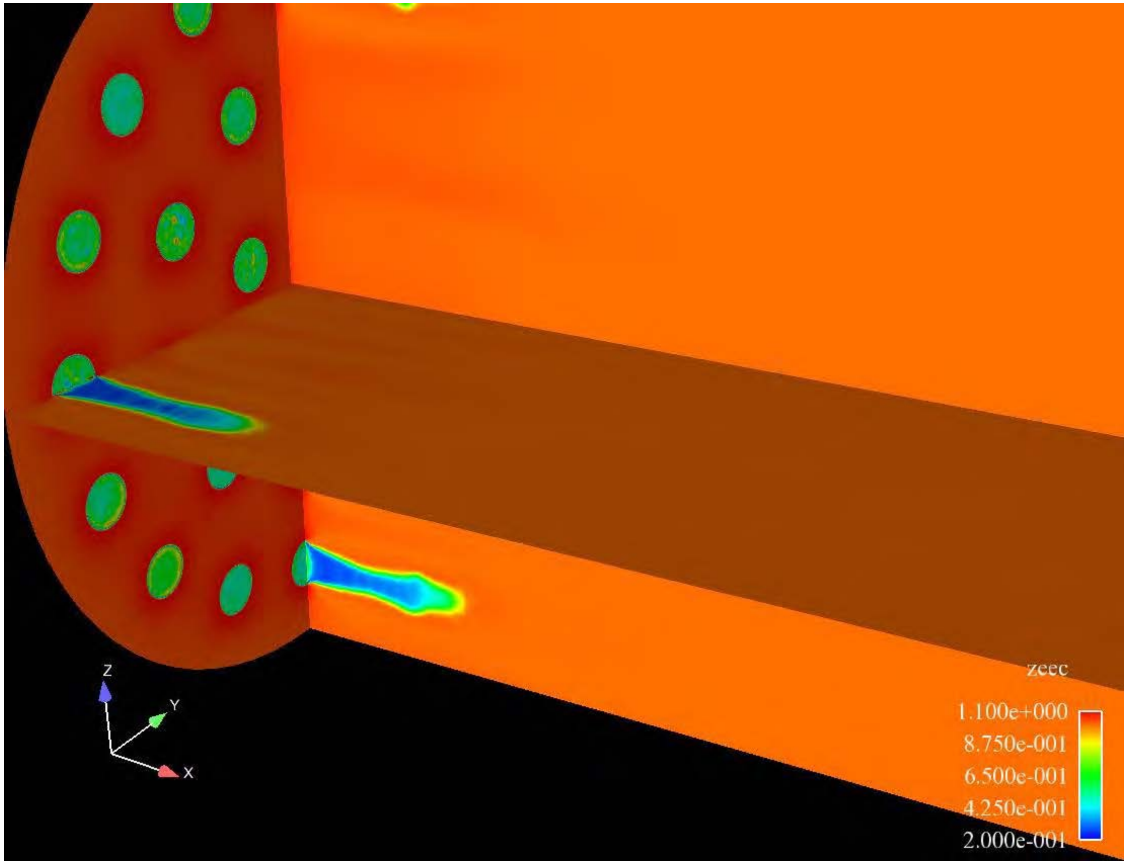


- Penn State 3-element Lox-hydrogen Test
- Approximately 900,000 Gridpoints
- Peng-Robinson Supercritical Fluid Equation Of State
- Mechanistic Finite-rate Combustion

Wall Heat Transfer Comparison for PWRFlow Simulation of 3-Element Chamber

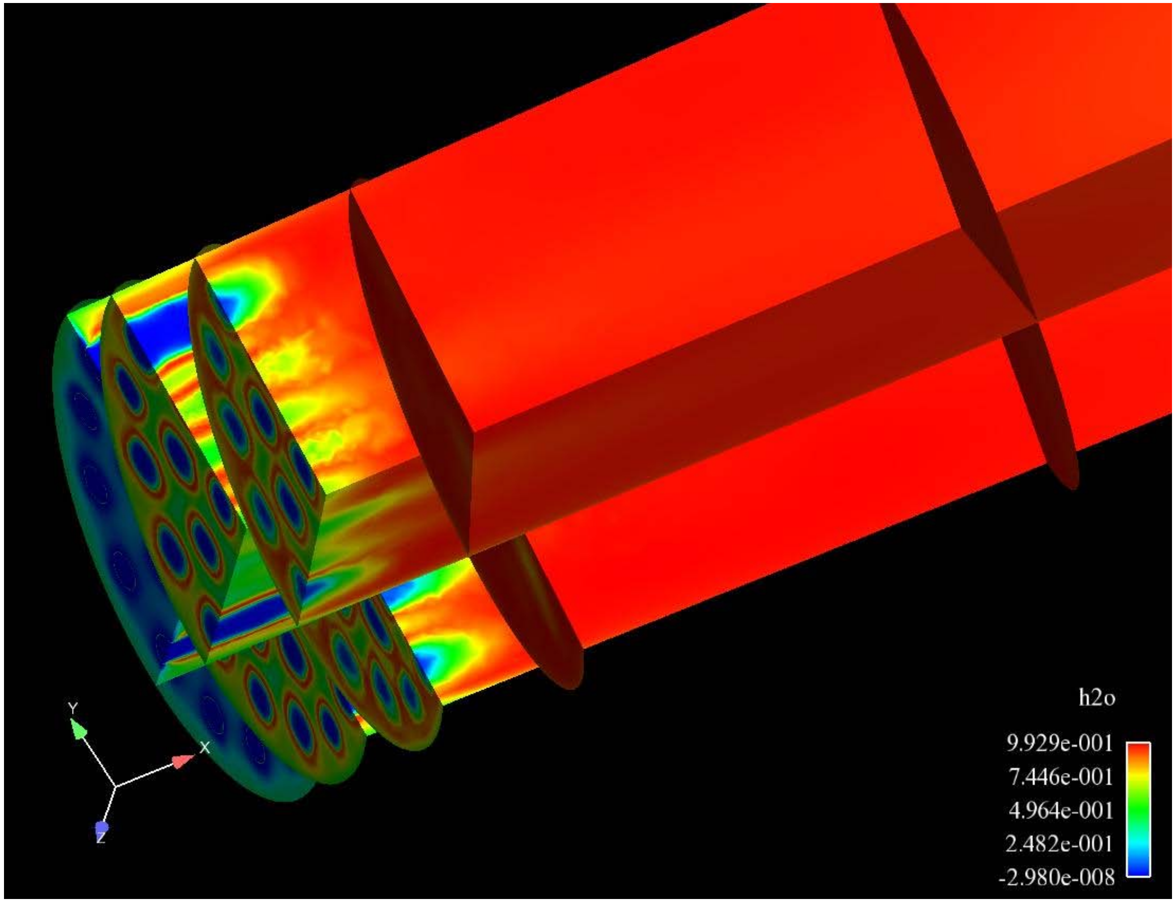


28-Element 40k-Calorimeter CFD Analysis Showing LOX Streams through z Contours



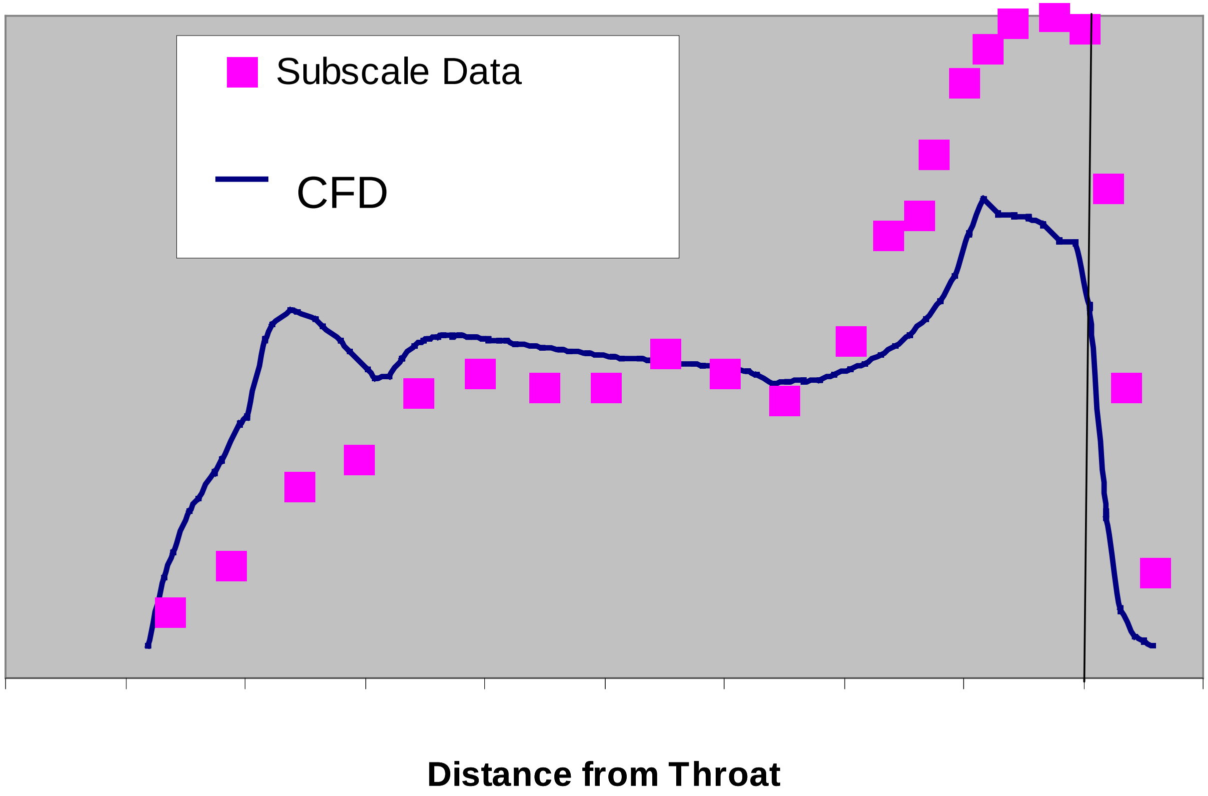
- 9,000,000 Gridpoint Computation with Fully Unstructured Grid
- Global Hydrogen–Oxygen Finite-rate Combustion
- Peng-Robinson Equation of State for Supercritical Fluids

H_2O Forms in Shear-Layer Between LOX and H_2

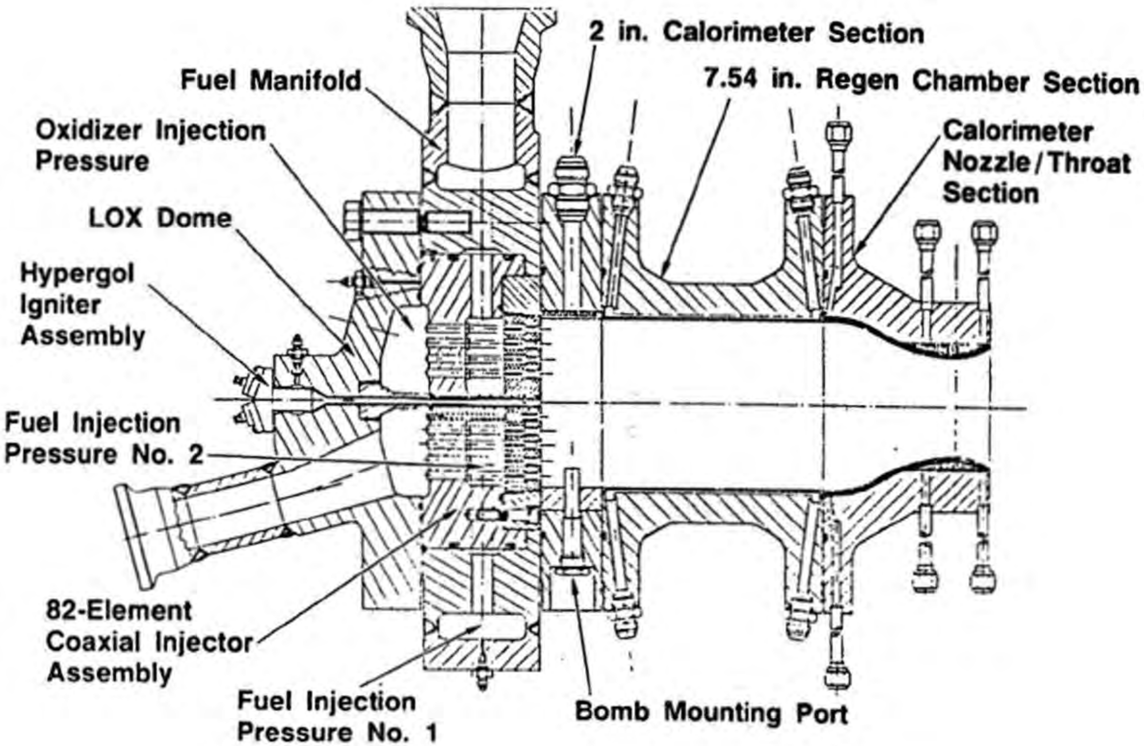


Comparison to Wall Heat Transfer for 40k Calorimeter Analysis

- Unstructured Grid Opened Up Too Quickly Downstream
- Mixing Rate Overpredicted in Near Field
- Wall Heat Transfer Underpredicted
- Grid Resolution Needs to Be Finer Near Throat to Capture Peak Heating



Validation Plan Includes 82-element Jensen LOX-Hydrocarbon Stability Tests



- “Final Exam” Validation through Hydrocarbon Boost Preburner and Main Injector data
- Midterm Exam through 82-element Jensen LOX-Hydrocarbon Stability Tests
  - Stability and Instability in Same Rig
  - Investigators at PWR
  - Methane Equal or Worse Case than RP

Summary

- Collaborators Bring Previous Technology into Program
  - PWR: Rocket Stability and RANS CFD Modeling
  - UTRC: Combustion Modeling
  - Georgia Tech: LES Combustion Modeling
  - HyPerComp: CFD Software Development
- SRR Completed on Program
- Validation Plan Defined
- Departure Code Being Distributed to Team Members

Acknowledgements

- Support Of The Air Force Research Laboratory On The ALREST-HFM Program
- Other Members Of The ALREST Team
  - Robert Jensen, Tim Hinerman, and Steve Barson at PWR
  - Jeremiah Lee, Chris Eckett, and Dusty Davis at UTRC
  - Ramakan Munipalli, Rohit Jain, and Zhining Liu at HyPerComp
  - Mathieu Masquelet and Nicolas Guezennec at Georgia Tech